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Integration of the energy recovery step in municipal wastewater treatment chain: a case study of Moshi municipality, Tanzania

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INTEGRATION OF THE ENERGY RECOVERY STEP IN MUNICIPAL WASTEWATER TREATMENT CHAIN: A CASE STUDY OF MOSHI MUNICIPALITY, TANZANIA

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master's of Environmental Science and Engineering of the Nelson Mandela African Institution of Science and Technology (NM-AIST)

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ABSTRACT

The energy demand which is expected to increase more worldwide has sparked the interest of researchers to find sustainable and inexpensive sources of energy. This study aims to integrate energy recovering step into municipal wastewater treatment plants ($MWWTP_S$) through anaerobic digestion. The anaerobic digestion of municipal wastewater (MWW) and then co-digestion with sugar cane molasses (SCM) to improve its organic content was conducted at 25 ^oC and 37 ^oC. The results showed substrate mixture containing 6% of SCM and total solids (TS) of 7.52% yielded higher amount of biogas (9.73 L/L of modified substrate). However, chemical oxygen demand (COD) of the resulting digestate was high (10.1 g/L) and pH was not stable hence needed careful adjustment using 2M of NaOH solution. This study recommends substrate mixture containing SCM (2%) and TS (4.34%) having biogas production (4.97 L/L of modified substrate) for energy recovering from $MWWTP_S$, since is found to have more stable pH and low COD residue (1.8 g/L) which will not hold back the MWW treatment process. The annual generation of modified substrate (662 973 m^3) is anticipated to generate about 16 241 m^3 of methane which produce up to 1.8 GWh and 8193 GJ per annum. The study concluded that biogas is among of the future fuel if the modern technology on anaerobic digestion is functional. Also the use of combined heat and power (CHP) engine for the conversion of biogas to heat and electrical energy increases the energy value of the wastewater.

(Keywords: Anaerobic digestion, Biogas, Municipal wastewater, Sugarcane molasses)

DECLARATION

I, VAILETH HANCE do hereby declare to the senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Name and signature of the candidates

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The above declaration is confirmed

Prof. Karoli Nicholas Njau

Signature: ______________________________ Date: __________________

Dr. Thomas Kivevele

Signature: ______________________________ Date: __________________

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CERTIFICATION

The undersigned certify that they have read the dissertation titled “Integration of the Energy recovery step in Municipal wastewater treatment chain: A case study of Moshi municipality, Tanzania” submitted by Vaileth Hance and recommended for examination in fulfillment of the requirement for the degree of Master’s in Environmental Science and Engineering (EnSE) of the Nelson Mandela African Institution of Science and Technology (NM-AIST). The work is reliable and has been done under our supervision.

Principal supervisor

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DEDICATION

This work is dedicated to my lovely husband; Robert Makori Hongo, my daughter Eunice Robert, my son John Robert and all family members. The inspiration and prayers from them are highly treasured.

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LIST OF ABBREVIATIONS AND SYMBOLS

$AWSP_S$	Anaerobic waste stabilization ponds
BOD	Biological oxygen demand
C/N	Carbon to nitrogen ratio
COD	Chemical oxygen demand
CHP	Combined heat and power
EWURA	Energy and Water Utilities Regulatory Authority
kWh	Kilowatt hour
MJ	Megajoules
MW	Megawatt
MUWSA	Moshi Urban Water and Sewerage Authority
MWW	Municipal waste water
MWWTPs	Municipal wastewater treatment plants
MWWS	Municipal wastewater sludge
NBS	National Bureau of Statistics
PSM	Power system master plan
SCM	Sugarcane molasses
TOC	Total organic carbon
TPC	Tanganyika Planting Company Limited
TS	Total Solids
VS	Volatile Solids
v/v %	Volume by volume percent
WSP_S	Wastewater stabilization ponds

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

The consumption of fossil fuels to encounter the increasing energy demand has led to severe environmental problems like acidic rains, global warming and air pollution in both developing and developed countries (Karekezi, 2002). These negative effects can greatly be reduced by using renewable sources of energy (Pavi, Kramer, Gomes & Miranda, 2017). While fossil fuels are depleting rapidly, the demand for energy is expected to increase by more than 50% by 2025 worldwide (Cheerawit *et al.*, 2012). This has subsequently led to increased research in attempts to develop sustainable, inexpensive, environmentally-friendly and renewable sources of energy to reduce the consumption of fossil fuels (Ellabban, Abu-Rub & Blaabjerg, 2014). Anaerobic digestion of both solid and liquid wastes is considered as one of the best significant renewable energy sources that offer the double benefit of treating wastes while generating energy at the same period (Demirbas, 2011).

The universal production of municipal waste water (MWW) was estimated to be 900 million m^3 per day in 2015 which increases every year along with population growth (Mateo-Sagasta, Raschid-Sally, & Thebo, 2015). Various methods are used for treating collected wastewater however the best method differ with the characteristics of cities, such as climatic conditions, topography of the area, wastewater pollution, and the price of land (Dos Santos, Barros & Tiago, 2016). Biological method of treating municipal wastewater in most of the developing countries such as Tanzania is mainly done in waste water stabilization ponds (WSP_S) systems which treat waste water naturally (Ho, Van Echelpoel & Goethals, 2017). In anaerobic ponds (AP_S) organic matter contained in wastewaters are decomposed by microorganisms in absence of oxygen to produce mixture of different gases like ammonia, hydrogen sulphide, carbon dioxide and methane (Koh & Shaw, 2017). This mixture is considered as the renewable and sustainable energy source in its right proportion.

Currently, there are 11 municipal wastewater treatment plants (MWWTPs) involved in wastewater assortment and management through the use of WSP_S to benefits merely 6.2% of the Tanzania’s population. Waste stabilization ponds receives about 407 488 m^3 of MWW per day (Kihila, Mtei & Njau, 2015). The MWW with typical organic matter of 1500-2000 mg

COD/L comprises sufficient chemical energy which can allow energy recovering (Tchobanoglous, Burton & Stensel, 2003). Anaerobic digestion of MWW collected at WWTPs for energy recovery can produce energy in the form of fuel and sometimes in form of heat and electricity. The technique reflected high environmental sustainability process of treating wastewaters. However, MWW is a much diluted mixture hence low emission of methane, higher methane solubility and unbalanced carbon to nitrogen (C/N) ratios (Guven *et al.*, 2019). Currently in order to achieve the energy recovering process, organic matter content is concentrated by bio flocculation conventional methods though they suffer from low removal efficiency, high energy consumption and expensive definitely for developing countries hence less applied (Lin & Yang, 2017). As such, there is a need to investigate ways to overcome these limitations by co-digesting MWW with materials containing high organic matter contents rich in carbons like sugarcane molasses (SCM) which is readily available, not too bulk and less expensive for higher biogas yields.

Sugarcane molasses are the main byproducts of sugar-refining industries and contain a high amount of sugars and nutrient minerals (Park *et al.,* 2010). They are commonly used as raw materials for alcohol production and livestock feeds (Laluce *et al.*, 2016). The SCM contain a large amount of organic matter due to their large content of sugars and high C/N ratios (Iqbal, Aftab, Aslam & Ahmed, 2014). Therefore, they can be used to adjust the C/N ratio of carbon-poor substrates such as MWW to maintain the equilibrium capacity of the bioreactors and enhance biodegradation for optimal production of biogas (Mata-Alvarez *et al.*, 2014). The produced biogas can reduce the greenhouse gases emission and use of fossil fuel. Also it can be used for lighting systems, heating , power supply to vehicles and co-generation of heat and electricity depending on the generation technology used (Dos Santos, Barros & Tiago, 2016).

There are various technologies in the market used to convert biogas directly into power (Surroop & Mohee, 2012). Including direct combustion of biogas in gas boilers which release heat energy in form of steam, also burning of biogas at high temperature in a combined heat and power generator (CHP) for simultaneous production of heat and power (Kaparaju & Rintala, 2013). Combine heat and power systems are of different capacities and compatible with anaerobic digesters although it is not commonly technology used in developing countries (Moya, Aldás, López & Kaparaju, 2017). Thus, the conventional technique can be used to estimate the available potential energy in MWW collected to the $MWWTP_S$.

In this research, the anaerobic decomposition of MWW and co-digestion with SCM as modifier under mesophilic conditions were evaluated in terms of cumulative biogas production, biogas yield, methane content, COD removal and stability of the process. Then the data of the mixing ratio with the smallest amount of SCM and low digestate COD was used to estimate the potential heat and electricity production. This was due to the fact that the integration of the onsite energy recovering step in MWW treatment chain doesn't consider only energy recovered but also the sustainability of the process to the environment.

1.2 Statement of the problem

Energy demand and wastes production are increasing globally. This is more relevant to Tanzania and the developing world due to the improved economic development and population growth. Regardless of intervention strategies made to rescue the energy demand in Tanzania, such as expansion of energy sources and importing from neighboring countries like Kenya (1 MW), Zambia (5 MW), and Uganda (10 MW), still energy deficit is a problem. Currently the available installed energy capacity of 1564 MW is not enough when compared with the current average electricity consumption of 108 kWh needed per capital per year. That's why Tanzania has a plan of raising the connected power capacity from 1564 MW to about 10000 MW by 2025. Diversifying the energy sources and to include other renewable sources, big and small, will be advantageous for Tanzania to reduce energy scarcity. The sources could include the anaerobic digestion of MWW collected to WSP_S because it contains large content of organic matter and continuously accessible in large quantity. Through the anaerobic digestion, onsite generation of energy in form of fuel and occasionally heat and electricity mighty be achieved and show environmental sustainability of using WSP_S. However, it is not commonly applied because the use of MWW directly for the anaerobic digestion is not economically feasible process as it has low methane production, higher methane solubility and unbalanced carbon to nitrogen (C/N). Therefore, there is a need to investigate ways to overcome these limitations, by introducing other source of organic content for codigesting the MWW to increase the biogas production which can be used to generate electricity and heat.

1.3 Rationale of the study

Energy is among of the prerequisite for economic growth. Its requirement increases the use of fossil fuel which contributes to environmental problems. Hence the urgent need to develop and exploit the native sources of energy such as biogas from MWW which is readily available in a country. This gives a reason of investigating the potentiality of exploiting the energy from the MWW collected to municipal treatment plants. Also the use of CHP engine for the conversion of biogas to heat and electrical energy increases the energy value of the wastewater and can be an incentive for wastewater treatment plants. Due to time limit and resources available only one type of wastewater was used in this study; however there are other types of wastewaters that may give more energy when codigested. Therefore, more research on the energy recovery from waste waters in form of biogas and its conversion to heat and electrical energy are fortified.

1.4 Objectives

1.4.1 General objective

To assess the potential of integrating energy recovering step in Municipal wastewater treatment value chain in Moshi municipal wastewater treatment plant, Kilimanjaro-Tanzania.

1.4.2 Specific objectives

(i) To establish the biogas production potential of wastewater from Moshi municipal wastewater treatment plant.

(ii) To optimize the biogas production conditions of wastewater from Moshi municipal wastewater treatment system. To establish the potential heat and electrical energy production from Moshi municipal wastewater treatment plants.

(iii) To establish the potential heat and electrical energy production from Moshi municipal wastewater treatment plants.

1.5 Research questions

(i) What is biogas potential of wastewater from Moshi municipal wastewater treatment plant?

(ii) What are the optimal conditions for the efficient biogas production from Moshi municipal wastewater treatment plants?

(iii) How much electric power can be generated from existing wastewater treatment system in Moshi municipality?

1.6 Significance of the study

The proposed study intended to expand the technology of recovering biogas from the $MWWTP_S$ and its conversion to heat and electrical energy as the environmentally friendly source of energy. It encouraged with the fact that the world is shifting towards renewable energy sources and biogas is among the renewable energy sources whose application gets increasing day to day. The construction of a biogas plants are fortified because the study has given the optimum condition of the feedstock for higher biogas yield. Apart from that the study will support the government effort of reducing the use of fossil fuels hence reduction of greenhouse gases emission to the atmosphere by providing the source biogas for different activities. If the study will be successfully implemented it will made the base line for the decision making by the government and private sectors to invest on biogas recovery from $MWWTP_S$.

1.7 Delineation of the study

The present study assesses the integration of the energy recovery step in Municipal wastewater treatment plants through anaerobic digestion. The anaerobic digestion of municipal wastewater from Moshi municipal wastewater treatment plant and its codigestion with sugarcane molasses was done to enhance higher biogas production. Also the use of combined heat and power (CHP) system to convert biogas into heat and electricity was investigated with the purpose of increasing energy value. The study was conducted in moshi municipal during dry season. Therefore, the findings may not be similar with findings from another season or different geographical area.

CHAPTER TWO

LITERATURE REVIEW

2.1 Waste stabilization pond/ lagoons for energy recovery

Waste stabilization ponds (WSPs) are constructed to remove the organic matter and microorganisms (pathogens) from the domestic, sewage, municipal run off and industrial waste matter (Ramadan & Ponce, 2003). It is the natural treatment technique commonly used in the tropical regions with warm climate like Asia, Latin America, Africa, and Middle East, which support its competence in removing water pollutants (Daelman *et al.*, 2012). However, WSP_S can work healthy within range of weather conditions and population sizes (Raschid-Sally, Carr & Buechler, 2005). Wastewater enters on one side of the WSPs spend a number of days within the pond as the rate of treatment is slow and exits on the other side of the pond as effluent. The system is always made up of one or many ponds in a series and each pond has the specific function in treating waste water. Waste stabilization ponds can be used alone or combined with other treatment processes. The effluent from the WSPs are emptied to the surface water or reused as irrigation water and other activities when it meets the required effluent standards (Kihila, Mtei & Njau, 2015). Anaerobic ponds collect untreated wastewater and are established to reduce solid particles entering the facultative and maturation ponds as a pretreatment process (Cruddas *et al.*, 2018). They have a smaller surface area with high depth normally 3-5m which restricts the accessibility of oxygen hence allow anaerobic decomposition that reduces the quantity of organic matter (BOD) out with effluent (Ho, Van Echelpoel & Goethals, 2017). The anaerobic biodegradation of the organic waste contained in the WSP_S can release mixture different gases to the atmosphere including ammonia, hydrogen sulphide, carbon dioxide and methane (Fig. 2) (Daelman *et al.*, 2012; Koh & Shaw, 2017). When gases mixture is in their right proportions they are considered as a biofuel. Even though anaerobic WSP_S were not planned for optimization of anaerobic digestion which include biogas collection (Heubeck &Craggs, 2010). The global production of municipal wastewaters projected to be 900 million m^3 per day in 2015 and has been increasing every year alongside the population growth (Mateo-Sagasta, Raschid-Sally, & Thebo, 2015). In Tanzania waste stabilization ponds receive about 407 488 m3 of municipal wastewater per day through the sewer network as shown by Fig. 3 (Kihila, Mtei & Njau, 2015). The collected wastewater is made up of energy resources and other water nutrients which can be retrieved for reuse (Verbyla, Oakley & Mihelcic, 2013). This is due to the reason that municipal wastewaters with typical organic matter of 1500-2000 mg COD/L contain potential chemical energy for energy recapture (Tchobanoglous, Burton & Stensel, 2003; Verbyla, Oakley & Mihelcic, 2013).

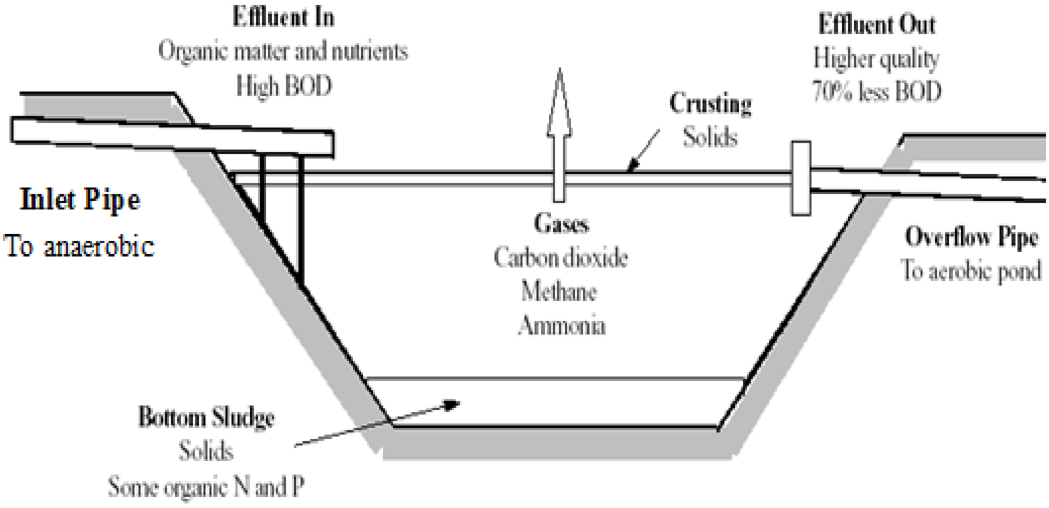

Figure 1: Operation of anaerobic pond by Ramadan and Ponce (2003)

Literatures have intensively explained the use of WSPs for wastewater treatment on the removal of COD, heavy metals N, P and pathogens but give scanty information on the application of contained biomass as a potential fuel (Dos Santos, Barros & Tiago, 2016). Regardless of the limited research/studies about WSPs on bioenergy recovery but it is considered as a simple method for the alteration from current zero energy- producing process to an energy- producing technology (Damasceno & Campos, 2000). The inadequate literature on anaerobic digestion of MWW for biogas production is caused by low production of methane due to imbalanced carbon to nitrogen (C/N) ratio, poor COD removal and higher methane solubility. All constraints are contributed with the fact that MWW is fairly dilute resource when related to the typical COD content of municipal wastewater sludge (MWWS) (Cheerawit *et al.*, 2012; Hagos, Zong & Liu, 2017). Therefore, optimization should be considered to raise energy recapturing from the WSPs.

In developing countries, anaerobic treatment of MWW for energy recovery is an appropriate technology as temperatures is favorable although only a few countries including India, South America, and lately Ghana (West Africa) use such technology (Verbyla, Oakley & Mihelcic, 2013). Tanzania as in many developing countries contributes negligible amounts of energy despite of receiving large amount of MWW in WSP_S with the considerable amount of organic matter. It is vital to integrate the energy recovering step into wastewater treatment system through the anaerobic decomposition to produce biogas which can be utilized for different activities including generation of heat and electricity.

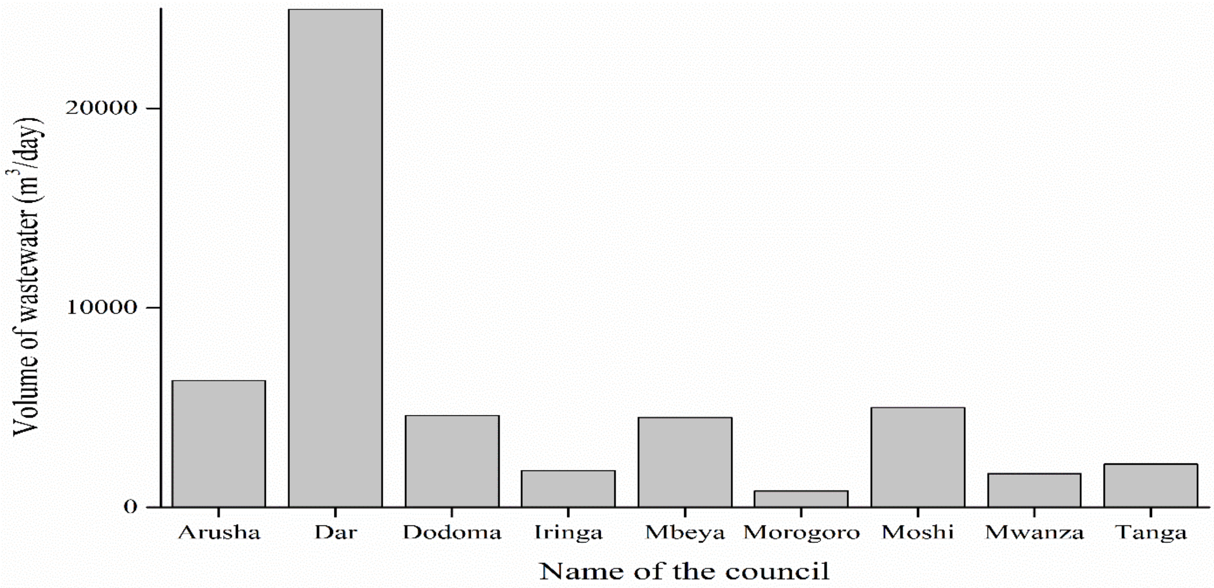

Figure 2: Amount of MWW collected through Sewer Network to WSP$_S$

2.2 Anaerobic digestion for biogas production and its optimal conditions

Anaerobic digestion includes sequence of progressions in which microbe's breakdown down decomposable (organic) materials in anoxic environment to produce mixture of different gases called biogas. Animal and human waste, food waste, agricultural waste, grass tops, waste paper, industrial waste and municipal waste are suitable for anaerobic digestion for biogas production (Mbuligwe & Kassenga, 2004; Rulkens, 2007; Roopnarain & Adeleke, 2017). Anaerobic digestion passes through 4 main steps namely Hydrolysis, Acidogenesis Acetogenesis and Methanogenesis as explained by Fig. 4 (Wang *et al.*, 2018).

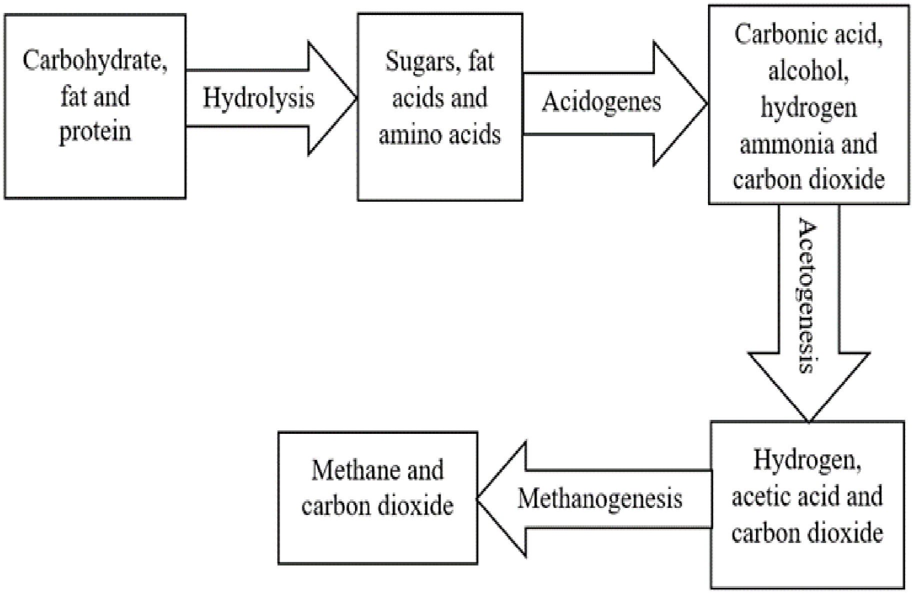

Figure 3: Stages of anaerobic decomposition for biogas production

The biogas yield varies with the nature and concentration of the feeding material. However, it is commonly made up of 50-75% methane (CH_4), 34-45% carbon dioxide (CO_2) sometimes with CO, N_2, H_2, H_2S, and O_2 in small amount (Kaparaju & Rintala, 2013). Biogas does not burn if it contains more than 75% of CO_2 (Noyola, Morgan-Sagastume & Lopez-Hernandez, 2006). Anaerobic decomposition has been effectively applied in the management of different types of wastes with biogas recovery. In developed countries like USA and Netherlands, it is a common to recover energy at $MWWTP_S$ through the anaerobic digestion of MWWS, even though they do not consider the use of MWW directly for the same purpose (Cheerawit *et al.*, 2012). The technique is very certainly novel in developing countries and Tanzania has never practiced despite the presence of large amount of MWW containing large content of the organic matter as a source of sustainable and renewable energy (Kothari, Tyagi & Pathak, 2010). Anaerobic digestion for biogas recovery from different kind of waste is a viable technology for producing renewable energy to reduce the gap of energy demand which grows exponentially worldwide (Panwar, Kaushik & Kothari, 2011). It is also reducing the use of the fossil which is unsustainable to ecological health and gets depleted rapidly (Karekezi, 2002).

Anaerobic digestion is strongly influenced with various factors such as Temperature, pH, organic matter, C/N ratio, VFA to alkalinity ratio and others. The factors should be in their optimal ranges for efficient production of biogas (Dobre, Nicolae & Matei, 2014).

Temperature, C/N ratio, VFA to alkalinity ratio and pH are the key factors for the effective functioning of the anaerobic digestion system.

2.2.1 Temperature

Anaerobic bacteria can develop in a broad range of temperature conditions which includes psychrophilic, mesophilic and thermophilic. The capability of anaerobic bacteria increases with the increase of temperature (Komemoto *et al.*, 2009). However, the process is recommended at the temperature of 35 °C -37 °C in the mesophilic range for higher production of methane (Vindis, Mursec, Janzekovic & Cus, 2009). Anaerobic digestion under methophilic range is stable as it is less sensitive to the temperature change unlike thermophilic process. Also requires a short retention time as compared to psychrophilic temperature range (Chae, Jang, Yim & Kim, 2008). Most of the reported anaerobic decomposition systems are operated in a mesophilic range because it is challenging to create and sustain high temperature in anaerobic digester at thermophilic range (Zamanzadeh *et al.*, 2016). Bacteria activities are affected directly with the gross change of temperature. Therefore, for the optimal operation of the biodigester the temperature should be controlled in a normal range (Jain *et al.*, 2015).

2.2.2 Carbon to nitrogen (C/N) ratio

The balance between C and N nutrients is required during anaerobic decomposition of waste to support the development of anaerobic bacteria and maintaining the stable environment in the digester (Romano & Zhang, 2008). Nitrogen is required for making the cell structure and carbon as the food for anaerobic bacteria (Jain *et al.*, 2015). The best C/N ratio for the maximum production of biogas is considered to range from 20–30 with the peak at 25. Though, it depends also on the type of feedstock used because optimal C/N ratio can vary even beyond the established optimal range (Romano & Zhang, 2008). The methanogenic bacteria are inhibited by the higher C/N ratios because of the nitrogen deficiency and low C/N ratios due to the carbon deficiency which brings about ammonia toxicity for the microbial population growth. Optimal C/N ratio had a good result on balancing the accumulated ammonia and volatile fatty acid (VFA) hence buffering the system and causing higher biogas yield and total organic carbon (TOC) utilization (Angelidaki *et al.*, 2018). Therefore, for the long term and stable working condition of the biodigester, the optimal C/N ratio of feedstock used should be known.

2.2.3 pH

The effect of pH depends on the step of the anaerobic decomposition. For instance hydrolysis can take place within pH range of 6.3 to 7.8 values, while on the other hand methanogenesis only continues in neutral pH. For maximum production of the methane the pH must maintained within the stated range (Khalid *et al.*, 2011). Any unexpected change in the pH is expected to cause disproportion in the bacterial population (Yarosz & Taylor, 2015).When the methanogenic rate is slower than the acidogenic rate, it results to acidic pH in anaerobic digestion systems which later lead to increase of the volatile fatty acids (Jain *et al.*, 2015). On the other hand, over existence of hydrolysis produce ammonia which result to alkaline. If the pH goes above 8.5, ammonia causes toxicity and death of methanogenic bacteria (Dobre, Nicolae & Matei, 2014). It is significant to monitor and retain the pH around the optimal range for the proper functioning of the anaerobic system.

2.2.4 Volatile fatty acid

Volatile fatty acid (VFA) level in biodigester is important factor to determine the stability of the anaerobic digestion process (Siegert & Banks, 2005). High accumulation of VFA is normally due to the presence of inhibitors or overloading of the organic waste which hinder the methanogen to remove VFA as quickly as they are formed during the anaerobic digestion. The outcome is the decrease of buffering capacity of the anaerobic process and accumulation of the acids which inhibit the hydrolysis/acidogenesis phase (Kameswari, Kalyanaraman, Porselvam & Thanasekaran, 2012). It has also been shown that the accumulation of the VFA can occur even when the pH is maintained within the optimal levels (Banks & Wang, 1999). The accumulation of VFA is counterbalanced with the level of alkalinity in the biodigester. To ensure the stability of anaerobic process it is important to monitor the relationship between alkalinity and volatile acids (Barampouti, Mai & Vlyssides, 2005). When the VFA to alkalinity ratio below 0.4 the anaerobic process is very stable, between 0.4-0.8 some instability will be observed during the anaerobic digestion process and at the VFA/alkalinity ratio above 0.8 affects the stability of the anaerobic digestion process significantly (Kameswari, Kalyanaraman, Porselvam & Thanasekaran, 2012).

2.3 Co-digestion

Co-digestion is when different types of organic wastes are digested together (Mata-Alvarez *et al.*, 2014). The shortage of one component from one type of waste can be compensated in another to improve C/N ratio so as to increase biodegradability and methane production (Astals *et al.*, 2015). Co-substrates are digested with the main feedstock for maximizing biogas production and/or as a treatment path for the concerned co-substrates. It has been reported that co-digestion have environmental and economic advantages by cost-sharing through treating several waste streams within one facility (Dareioti *et al.*, 2009). Co-digestion can minimize the inhibition effect of certain constituents of the mixture, optimize the amount of moisture in the biodigester feed, decreasing release of greenhouse gases to the sky, balance the nutrients needed for the active biodegradation hence high process stability (Hagos, Zong & Liu, 2017). Codigestion can increases the generation of biogas by 25% to 400% related to anaerobic digestion of the same single substrate (Hagos, Zong & Liu, 2017).

From the $MWWTP_S$, codigestion for the purpose of increasing biogas production is normally done by the use of wastewater sludge with other kind of waste including organic components of municipal solid wastes (Sosnowski, Wieczorek & Ledakowicz, 2003), yeast waste and restaurant waste (Zitomer, Adhikari, Heisel & Dineen, 2008), fat oil and grease (Li, Champagne & Anderson, 2015), food waste (Zahan, Othman & Rajendram, 2016), glycerin and dairy waste (Bodík, Sedláček, Kubaská & Hutňan, 2011), maize straw and cow manure (Wei *et al.*, 2019), slaughter-houses (Borowski & Kubacki, 2015), microalgae (Thorin, Olsson, Schwede & Nehrenheim, 2018), cheese whey and fruit waste (Hallaji *et al.*, 2019), industrial waste and kitchen solid waste (Minale & Worku, 2014), and brewery sludge (Pecharaply, Parkpian, Annachhatre & Jugsujinda, 2007) to mention some. Yet, there is the limited information on the codigestion of the raw MWW entering the anaerobic waste stabilization ponds with other organic waste for energy recovery (Shoener, Bradley, Cusick & Guest, 2014). Therefore, more investigations on codigestion of MWW with other organic materials like sugar cane molasses for production of biogas are encouraged.

Sugar cane molasses (SCM) is among of the main remnants produced in considerable amount from sugar refining industries which contains high amount of sugars and nutrient minerals (Park *et al*., 2010). It is commonly used as the raw materials for making alcohol and livestock feeds (Laluce *et al.*, 2016). Tanzania produces more than $1.1x10^4$ tons of molasses per year. Tanganyika Planting Company Limited based in Kilimanjaro region is among of the four major sugar refining industries which produce about $4x10^4$ with the excess of $1.3x10^4$ tons of molasses per year. Its composition varies depending on cane variety, soil type, climatic condition, and classification method (Dotaniya *et al.*, 2016) as indicated in Table 1.

Table 1: The constituent of sugarcane molasses

Composition of molasses	%
Sucrose	30-35
Glucose and fructose	10-25
Moisture	23-23.5
Ash	16-16.5
Calcium and potassium	4.8-5
Non –sugars compounds	2-3
Other mineral content	1-2

Dotaniya *et al.* (2016)

Sugarcane molasses contains large quantities of organic matter that can be used to enhance biogas production from substrates poor in carbon content thus low C/N ratio e.g. MWW (Iqbal, Aftab, Aslam & Ahmed, 2014). Few studies have used SCM as a single substrate to enhance production of biogas (Dubrovskis & Plume, 2016) or in co digestion with other organic waste (Lee *et al.*, 2014).

2.4 Biogas potential for energy production

The calorific value of biogas depends on the digested feedstock and the anaerobic decomposition process which enhance high accumulation of methane content. The amount of methane determines the energetic potential of biogas (Salomon & Lora, 2009). Biogas with 65% of methane contains a high calorific value of 26 MJ/m^3 (Panepinto *et al*., 2016). In the production of thermal and electrical energy, 1m^3 of biogas containing methane content of 50-60% can yield 2.1 kWh of electrical energy and 22 MJ heat energy (Ziemiński & Frąc, 2012). From calorific value of 1 m^3, 0.77 m^3 of natural gas, 1.1 kg of hard coal and 2 kg of firewood with calorific value of 33.5 MJ, 23.4 MJ and 13.3 MJ respectively can be substituted (Arbon, 2002). Biogas has the higher calorific value compared with other fuels as shown in Table 2**.**

Table 2: Thermal energy of biogas compared with other fuels

Fuel type	Unit	Equivalent in unit volume	Thermal energy(MJ)
Biogas 60% methane	m^3	1	21.49-23.88
Dry wood	kg	2.85- 2.34	7.53-9.20
Lignite	kg	2.85-1.35	7.53-15.89
Coal dust briquettes	kg	1.28-0.76	16.73-28.45
Natural gas	kg	0.6	35.56
Tar	kg	0.55-0.54	39.32-39.74
Fuel radiator	kg	0.54-0.53	39.74-40.58
Diesel fuel	kg	0.51-0.47	41.84-46.02
Liquefied petroleum gases	kg	0.23	92.04

Siegert and Banks (2005) and Sibiya and Muzenda (2014)

2.5 Applications of biogas and conversion technologies

Biogas can be used for the equivalent purposes done by using natural gas (Qian *et al.,* 2017). In developing countries as a green energy source is used for lighting and cooking specifically in rural areas (Angelidaki *et al.,* 2018). Biogas can be burned directly for the production of heat and steam in large boilers, production of electricity and heat in the combined heat and power (CHP) unit for the local grid, fuel for vehicles, upgraded and used in gas supply network, chemical production and in making biofuels (Kadam & Panwar, 2017). Basing on environmental perspective, biogas capture for energy recovery reduces production of greenhouse gases, enhance the recirculation of organic waste and reduce the use of artificial fertilizers (Zhou, Chaemchuen & Verpoort, 2017). When biogas is compared to the other green source of energy like solar and wind, it is easily and quickly accessed on demand (Hahn, Krautkremer, Hartmann & Wachendorf, 2014).

From the WSP_S, onsite energy recovery can be done through the anaerobic digestion for biogas production then conversion and intensification of the biogas for energy generation with CHP system (Mo & Zhang, 2013). Decentralized heat and power systems is cost-effective because they reduce transmission and distribution costs of energy (Bouffard & Kirschen, 2008). The unit cost of biogas-based electricity should be less than supplied by the electricity boards even though it depend on capital costs of the system and economic benefits derived from biogas as well as effluent produced (Neto, Carvalho, Carioca & Canafistula, 2010). Generation of electrical power and heat from biogas as a decentralized source of bioenergy has been adopted in several developed countries including Netherlands, Australia, Finland, France, German, Norway, Korea, Switzerland, Malaysia, Denmark, United Kingdom, China, India, Nepal and others (Salomon & Lora, 2009). However, in African countries the technology is rarely applied. In Tanzania it has been applied in few established biodigesters including sisal waste energy plant – Hale, Tanga (Sarakikya, Ibrahim & Kiplagat, 2015), but never been applied on the WSP_S treating MWW. Therefore, the potentiality of integrating energy recovery step by codigesting the MWW with other organic materials for biogas production and its conversion to heat and electrical energy is high.

Various encouraging technologies including proton exchange membrane fuel cells and solid oxide fuel cells are used to generate electricity with higher conversion efficiency. Though, they are highly affected with the carbon dioxide content in a biogas when compared to combined heat and power (CHP) generator (Corigliano, Florio & Fragiacomo, 2011). Combine heat and power generators are very common for upgrading biogas to produce electricity which can be distributed to grid and heat for heating and keep the digester temperature at the desired level (Dereli, Yangin-Gomec, Ozabali & Ozturk, 2012). Different size of the CHP system using gas turbines unit (500 kW to 300 MW) shows they can work with the anaerobic digesters of different capacities although it is not commonly used in developing countries (Jekayinfa, Linke & Pecenka, 2015). The gas turbines which use the CHP engine to convert biogas with electricity efficiency of 35-40% and heat 45-50% is available and commonly used (Jørgensen, 2009; Jekayinfa, Linke & Pecenka, 2015).

2.6 National energy demand

Different sources of energy are found in Tanzania including geothermal, solar, uranium, hydro, wind, biomass, natural gas, coal, tidal and waves (Sarakikya, Ibrahim & Kiplagat, 2015). However, traditional fuels like wood and charcoal from solid biomass are used as the primary energy for more than 85 % (Kilabuko & Nakai, 2007). The capacity of the country in electricity generation is 1564 MW. Among the available electrical energy 1438.24 MW are produced from the main grid and 125.9 MW from the min grid producers and imports from neighboring countries (Sumari, Shao & Kira, 2018). From the main grid generation capacity, hydropower contributes about 35% whereas thermal energy natural gas and oil contributes

33% and 32% respectively. Currently about 24% of the Tanzania total population have access to electricity with low per capital intake of 104.79 kWh per year (Bishoge, Zhang & Mushi, 2019).

The power system master plan (PSM) predicts that, the need of electricity in Tanzania will increase by more than 75% by 2035 (Chaplin *et al.*, 2017). Tanzania national development vision of being middle income country in 2025 shows the energy demand and connected customers will increase significantly to reach 7400 MW by 2035 which is much higher compared predicted 4700 MW by 2025 and 1000 MW in 2013 (Chaplin *et al.*, 2017). Various sources particularly natural gas and hydro exploitation should be maximized so as to increase the installed power capacity beyond 10000 MW by 2025 (Sumari, Shao & Kira, 2018). Due to growing energy demand there is the need of investigating other renewable energy sources as alternative to reduce the energy demand and environmental challenges (Dos Santos, Barros & Tiago, 2016).

2.7 Energy recovery from municipal wastewater treatment plants

Municipal wastewater treatment plants (WWTPs) are useful constructed tool to protect the community health and sustainability of the ecosystem. Waste water treatment plants were made to make sure the effluents meet the required standard and energy recovery was not the main concern, so far this has been changing in previous years (Panepinto *et al.*, 2016). Recently the $WWTP_S$ are progressing to be resource and energy recovering facilities. The energy proportion consumed by $WWTP_S$ differs from one country to another, it is between 1-5 % in European countries and USA (Longo *et al.*, 2016) and 0-3 in Africa (Roopnarain & Adeleke, 2017) depending on the technology used.

Municipal wastewater treatment plants can be enhanced via innovative process modifications and upgrading wastewater treatment technique to achieve energy positive operation or energy neutrality through anaerobic digestion for biogas recovery (Wett, Buchauer & Fimml, 2007). However, MWW is a much diluted mixture hence its organic matter content is concentrated by bio flocculation to achieve energy recovering process (Guven *et al.*, 2019). Various treatments for concentrating organic matter are applied worldwide including conventional primary settling, chemically enhanced primary treatment, high-rate activated sludge process and others (De Feo, De Gisi & Galasso, 2008). These methods suffer from low removal efficiency, high energy consumption and expensive definitely for developing countries hence less applied (Lin & Yang, 2017). There are some experimental studies on the codigestion of MWW and food waste, the result shows there was the increase of organic matter in influent MWW up to 70% (Moñino *et al.*, 2017). However, the use of grinders to minimize the particles size of the food materials is another limitation as it consume a lot of energy which reduce its energy potential (Guven *et al.*, 2019). Therefore, this study aimed at integrating the energy recovering step at the $MWWTP_S$ by introducing the source of organic matter direct to the MWW to improve its organic matter content for the feasible anaerobic process.

CHAPTER THREE

MATERIALS AND METHODS

3.1 The study site and treatment system

This research was conducted at Moshi Municipality wastewater treatment plant found in the Northern part of Tanzania situated in Kilimanjaro region. Moshi municipality treatment plant is managed by Moshi Urban Water and Sewerage Authority (MUWSA). The Sewer Network for municipal wastewater collection covers 46% of Moshi municipality which is the highest amount in Tanzania (Kihila, Mtei & Njau, 2015). However, for the areas without sewerage system wastewaters sludge are received through septic pump trucks. The Moshi municipality wastewater treatment plant use WSP$_S$ designed to carry 4500 m^3/d, it contains one anaerobic pond, two facultative ponds and six maturation ponds with its layout as shown in Fig. 5 (Kihila, Mtei, & Njau, 2015). The annual average inflow to the WSP$_S$ (4221.2 m^3/d) and its characteristics were as shown in Table 2**.** The outflow is estimated to be 2452.6 m^3/d.

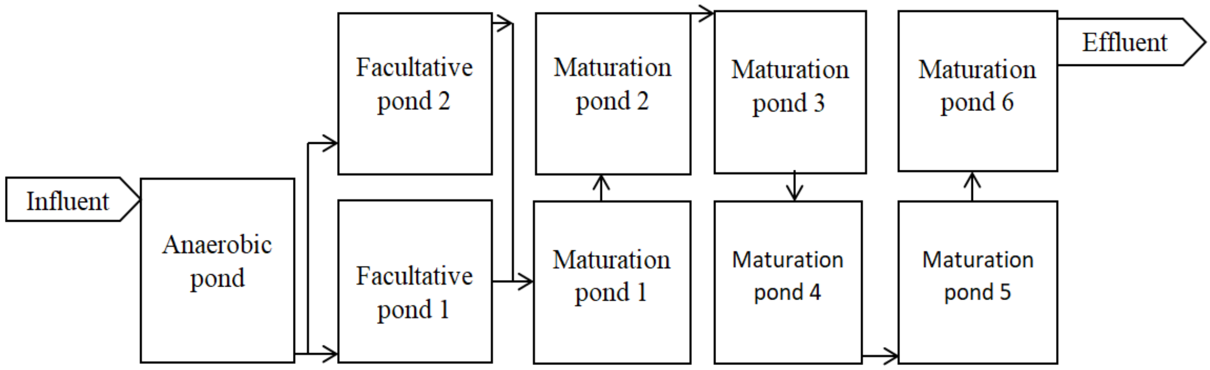

Figure 4: Schematic diagram of Moshi treatment system

3.2 Co-substrates and inoculums

Municipal waste water used in this study was obtained from the inlet of anaerobic pond of Moshi municipal wastewater treatment plant in the Kilimanjaro region, Tanzania. Sugarcane molasses were collected from Tanganyika Planting Company Limited (TPC) in Moshi, Tanzania which produces excess of 1.3 x 10^4 tons of SCM per year and is situated 21 km south-west of the municipal wastewater treatment plant. The inoculum was obtained from an anaerobic digester treating cattle manure as its feedstock at Kikwe village in Arusha, Tanzania. Cattle manure is considered as a good inoculum because it has a wide diversity of microorganism and optimal C/N ratio which ensures the sufficient level of hydrolytic and methanogenic activity in a wide range of substrates. The substrates and inoculum for the anaerobic digestion were individually homogenized by shaking for approximately 4 minutes and subsequently stored in a refrigerator at 4 °C until the time of use (Wang *et al.*, 2012). The characteristics of substrates and inoculum are shown in Table 2.

3.3 Batch experimental procedures

In this study the production potentials of biogas from anaerobic decomposition of MWW and the co-digestion of MWW and SCM as a modifier were determined. The experiments were conducted in the laboratories of Nelson Mandela African Institution of Science and Technology in Arusha, Tanzania.

3.3.1 Anaerobic digestion of municipal wastewater

The tests were done in anaerobic batch reactors with the working volume of 1L operated at the mesophilic temperature of 25 ^{o}C±1 and 37 ^{o}C±1. To initiate the anaerobic digestion of the MWW, 10% (*v/v*) of inoculums were added to anaerobic digesters and then mixed with 90% (*v/v*) of MWW to make 1 L (Chae, Jang, Yim & Kim, 2008). For the stability of anaerobic digestion pH of the feedstock were adjusted to 7.3 by using 2 M of NaOH. Then the biodigester were made air tight using rubber stoppers after flushing by nitrogen gas for 10 minutes to sustain anaerobic environment inside digestate bottles. An outlet from the biodigester was connected with 10 mm cylindrical tube for collecting biogas in measuring cylinder with volume of 1000 mL. The daily production of biogas was obtained through measuring the displaced water. The volume of biogas (mL) produced from each digester were recorded daily and methane composition (%) were determined after every 3 days. The bio digesters were gently shaken for the purpose of mixing the floating layer regularly once a day. Biogas production was monitored periodically until gas production became negligible.

3.3.2 Co-digestion of municipal wastewater and sugarcane molasses as a modifier

The procedures used for the anaerobic digestion of MWW were also used in the codigestion of the MWW and SCM. The codigestion experiments were conducted at the mesophilic temperature of 37 ^{o}C±1. One liter (1L) of modified substrates of MWW and SCM which were prepared with the mixing ratios of (v/v %) 100:00, 98:02, 96:04, 94:06, 92:08 and 90:10

to make the C/N ratios of 10.6, 15.7, 20.0, 23.8, 27.1 and 30.4 respectively. For the steadiness of the anaerobic decomposition, the pH of the modified substrates were adjusted and maintained between 6.5 and 7.5 by using 2M of NaOH. The laboratory set up for the anaerobic digestion process using MWW and its co-digestion with SCM is as shown in Fig. 6.

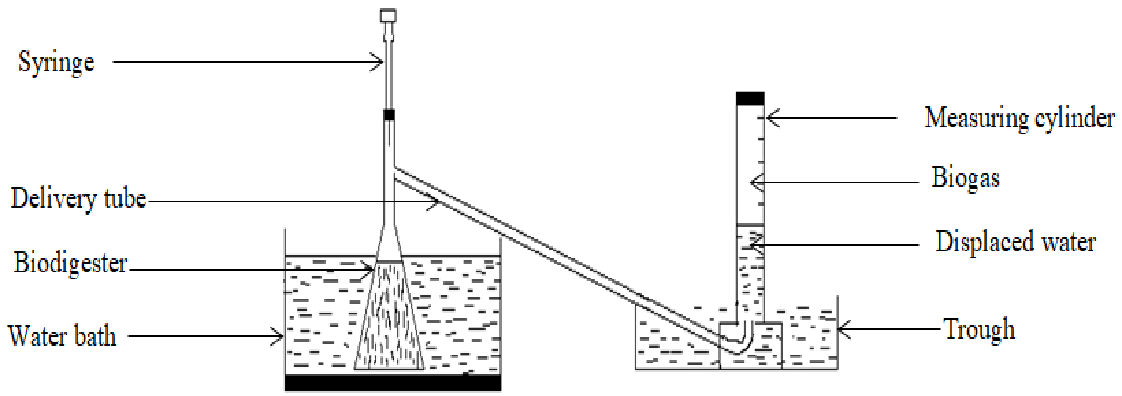

Figure 5: A sketch of the laboratory set up for the anaerobic digestion

3.4 Analytical procedures

Municipal waste water samples collection was done by composite sampling technique using plastic bottles and preserved in the cool box for chemical analysis. Sampling and characterization was done after every 5 days for six weeks in dry season. Physical-chemical parameters including temperature, dissolved oxygen (DO), pH, electrical conductivity (E.C) and total dissolved solid (TDS) were measured on site using HANNA Multiparameter (HI 9829).

Chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen (TN), total carbon (TC), total solid (TS), volatile solids (VS), total moisture (TM), total volatile fatty acid as acetic acid (VFA), total alkalinity as calcium carbonate (alkalinity) and pH were analyzed during anaerobic digestion experiments. The COD concentration was determined by close refluxing method using spectrophotometer (DR 2800). Biological oxygen demand (BOD_5) measurement was done using the respirometric method for five days using OxiTop TS 606/2-i system. Total carbon and total nitrogen were determined by Thermo Scientific FLASH 2000 HT Elemental analyzer. Carbon to nitrogen ratios of the modified substrates were determined by using the Cornell compositing method (Chen *et al.*, 2011). The total solids (TS) and total moisture (TM) were determined gravimetrically by drying the homogenized samples at 105 °C for 24 hours. The volatile solids (VS) fractions were determined gravimetrically by incinerating in a muffle furnace at 550 °C for 1 hour. The calculations for solids determination were done according to (Sluiter *et al.*, 2008). Volatile fatty acids and alkalinity were determined by simple titration method (Siedlecka *et al.*, 2008). The pH and temperature were measured using a pH meter (Beckman pH 211). Instruments were first calibrated before using by standard solutions as per standard methods for the examination of water and wastewater (APHA, 2012). The biogas content analysis was done by using the biogas analyzer (DR 5000). Statistical data analysis was done by using Origin Pro 8 to analyze biogas production potential from different mixing ratios and their correlation.

3.5 Biogas yield

The biogas yield of each mixed ratio (L/g COD) were calculated through the ratio between the cumulative volume of biogas to the amount of COD added to the biodigester times the volume of the substrate mixture used as shown in Equation 1.

$$Y = \frac{V_{g-Total}}{(COD_i) x\, V_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where

Y = biogas yield (mL/gCOD)

$V_{g-Total}$ = cumulative volume of biogas (mL)

COD_i= initial COD of substrate (g/L)

V_s = volume of substrate used (L)

Also COD removal efficiency (%) was calculated by taking the ratio between the COD removed by the digester and the COD added to the digester in percentage as shown in Equation 2.

$COD\ removal\ (\%) = \left(\frac{COD_i - COD_f}{COD_i}\right) x100$ .... (2)

Where

COD_i = Initial COD (g/L)

COD_f = Final COD (g/L)

3.6 Heat and power estimation

The actual energy recovery potential from Moshi municipal treatment plant was calculated based on the performed experimental study. Because theoretical biogas yields assume the degradation of the entire COD hence misleading conclusion. The amount of biogas produced per m^3 of substrate mixture was estimated by comparing the amount of biogas produced from the substrate used to the amount of substrate could be formed from Moshi municipal wastewater treatment plants per day. Then the biogas produced was used to determine its heat and electrical energy potential. The gas turbines which use the combined power and heat engine to convert biogas to heat and electricity with an efficiency of electricity 35-40%, and heat 45-50% were used as the conversion technology for the estimation of the energy produced (Jørgensen, 2009; Jekayinfa *et al.*, 2015). Estimation was done by considering the smallest efficiency in both heat and electricity (Equation 3 & 4) respectively as explained in (Salomon & Lora, 2009). In equations units of conversion were also included; the amount of heat produced from 1 m^3 of pure methane (100%) is 39.8 MJ which is equivalent to 11.06 kWh (Jørgensen, 2009). The UnitJuggler unit converter was used to compare the electrical energy produced from MWW to the other commonly used fuels.

$TH_{biogas} = C_{CH4} \times CV_{CH4} \times TV_{biogas} \times \epsilon$ .... (3)

Where

TH_{biogas}	=	Estimated total heat produced by the total volume of biogas (MJ)
C_{CH4}	=	Average content of methane (%v/v)

CV_{CH4}	=	Calorific value of pure methane (MJ/m^3)
TV_{biogas}	=	Estimated total volume of biogas (m^3)
$\in$	=	Conversion efficiency of CHP system (%)

$$TP_{biogas} = C_{CH4} \times TP_{CH4} \times TV_{biogas} \times \in \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where

TP_{biogas}	=	Estimated total power produced by the total volume of biogas (kWh)
C_{CH4}	=	Average content of methane (%)
TP_{CH4}	=	Total power of pure methane (kWh/m^3)
TV_{biogas}	=	Estimated total volume of biogas (m^3)
$\in$	=	Conversion efficiency of CHP system (%)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Establishment of the biogas production potential from municipal wastewater

Wastewater collected to Moshi MWWTPs was characterized in order to determine its capability towards biogas production through anaerobic digestion. The annual average characteristics of MWW were similar to the average characteristics measured during the study as shown in Table 3.

Results showed the range of BOD and COD were between 460 - 1450 mg/L and 990 - 2600 mg/L respectively. It was enough amounts of the organic materials for the anaerobic decomposition to take place and generate the biogas. Studies show that waste water with the BOD of at least 400 mg/L and COD of 1500 mg/L is capable of producing biogas (Tchobanoglous, Burton & Stensel, 2003). In addition, MWW with typical organic matter of 1500 - 2000 mg COD/L contain a potential chemical energy for energy recovery (Tchobanoglous, Burton & Stensel, 2003) provided that other main parameters including pH, C/N ratio, total solids and temperature are in optimal range.

For the microorganism to be active in the biodigester the pH of the biodigester should be maintained between allowable range of 6.3 to 7.8 (Palatsi *et al.*, 2009). The pH of the MWW ranged from 6.2 and 7.3 which slightly deviated from the optimum range, therefore, before the anaerobic digestion the pH was supposed to be optimized and maintained throughout the anaerobic process because any change of the pH can cause disproportion in the bacterial population (Zonta, Alves, Flotats & Palatsi, 2013).

The average C/N ratio of 10.2 was below the optimum recommended ratio reported by different literatures of 20: 1 - 30:1 with the optimal ratio of 25:1 (Jain *et al.*, 2015). Therefore, the need of optimizing it by carbon rich substrate for anaerobic bacterial growth in an anaerobic digestion system was observed. Carbon is required as the food for the anaerobic bacteria and nitrogen as the electron acceptor in cell formation the process (Wang *et al.*, 2012). Therefore, it must be optimized by carbon rich substrate for anaerobic bacterial growth in an anaerobic digestion system.

The MWW total solids (TS) were very low compared with similar studies where municipal wastewater sludge was used as the feedstock for maximum production of biogas. Total solids explain the potentiality of the substrates in anaerobic digestion because the biogas and methane yield depend on biodegradable transformation of its volatile matter (Buffiere, Loisel, Bernet & Delgenes, 2006). Therefore, municipal waste water is very dilute to undergo anaerobic digestion for better biogas generation.

Table 3: Characteristics of the raw MWW entering the anaerobic ponds

Parameter	Annual average (2018) Mean ± standard deviation	During the study Mean ± standard deviation
pH	6.7 ± 0.6	6.7 ± 0.5
TDS(mg/L)	926.1±53.9	1134 ± 131.9
BOD(mg/L)	840.6±49.1	968.3 ± 335.9
COD(mg/L)	1559.1±86.5	1898.3 ± 540
TS (mg/L)	N.D	1868.7 ± 237.6
TSS(mg/L)	N.D	734.6 ± 136.6
VFA (mg/L)	N.D	87.9 ± 17
Total N (%)	N.D	3.6 ± 0.2
Total C (%)	N.D	37.1 ± 3.6
C/N ratio	N.D	10.2 ± 0.8

ND =Not determined

Basing on the characteristics and potentiality of MWW on biogas production, the inevitability of enhancing it for the optimal production of biogas was observed. Among other materials for the optimization, SCM (modifier) was used due to its characteristic of being highly biodegradable, with volatile solids of 86.71% and low moisture content of 17.8% which suit with the dilution nature of the MWW. Moreover, higher C/N ratio of 64.9:1 was large enough to change the C/N ratio of MWW and establish the optimum C/N ratio for anaerobic co-digestion.

The volatile solids, pH and C/N ratio of the inoculum were in the optimal range for the ideal biogas production. The characteristics of used MWW for anaerobic digestion, SCM as a modifier in co-digestion and inoculum were as shown in Table 4.

Table 4: Characteristics of the substrates used for the anaerobic digestion

Characteristics	MWW	SCM	Inoculum
Ph	6.15	5.8	7.34
Total solids (TS) (%)	2.76	82.2	28.31
Total volatile solids (TVS) (%)	78.85	86.71	67.28
Total moisture (%)	97.24	17.8	71.69
Ash (%)	21.15	13.29	32.72
Total carbon (%)	36.53	37.62	38.47
Total nitrogen (%)	3.44	0.58	1.61
C/N Ratio	10.6:1	64.8:1	23.8:1
COD (g/L)	2.2	620	N.D
BOD (g/L)	1.2	N.D	N.D

ND=Not determined

4.2 The effect of temperature on cumulative biogas yields from municipal wastewater

From the anaerobic digestion of the MWW 1.37 L and 1.46 L of biogas were produced from 1L of the substrate used at the temperature of 25 ^{o}C and 37 ^{o}C respectively. The production at 25 ^{o}C was less by 6.5% when compared with that at 37 ^{o}C as shown by Fig. 7. This result were comparable to other studies which found high production of biogas at higher digestion temperature (Bouallagui *et al.*, 2004; Chen *et al.*, 2016). The retention time was reduced from 11 days at 25^{o}C to 8 days at 37 ^{o}C indicating that the activity of anaerobic bacteria was faster at the temperature of 37 ^{o}C compared to that at temperature of 25 ^{o}C. It is known that biogas production and its methane content normally increase with the increasing of temperature (Komemoto *et al.*, 2009; Ghatak & Mahanata, 2018). Therefore, there is inevitability of maintaining the methophilic temperature of 37 ^{o}C during the co-digestion to optimize the biogas production.

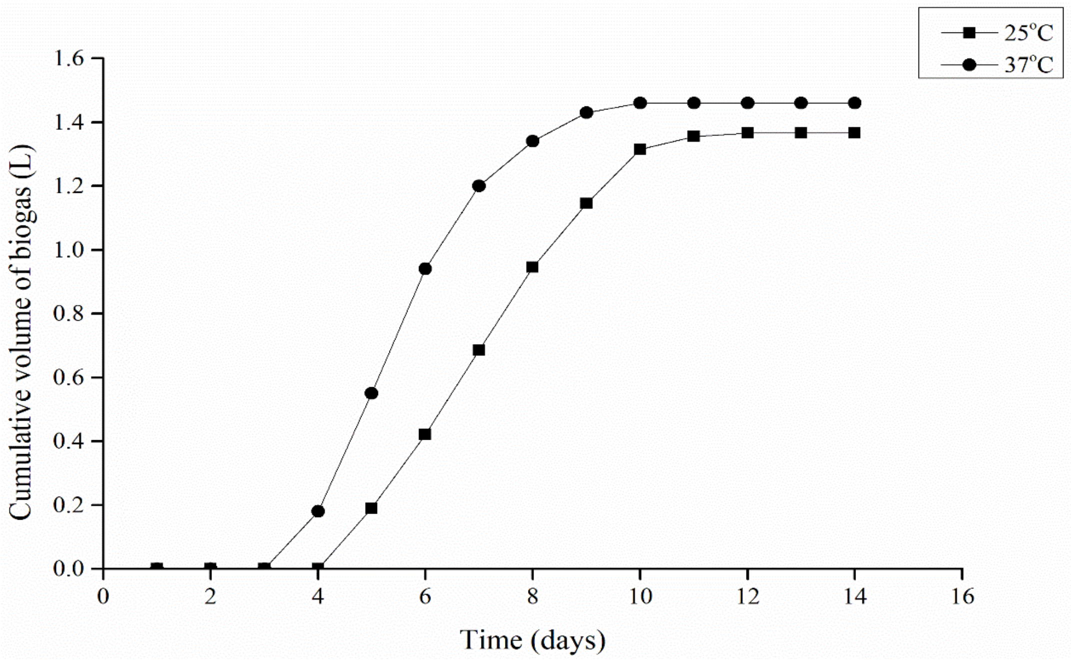

Figure 6: Effect of temperature (^{o}C) on cumulative volume of biogas

4.3 Effect of modification of municipal wastewater on carbon to nitrogen ratio and total solids

Table 2 shows that SCM was, highly biodegradable with volatile solids of 86.71% and low moisture content of 17.8% which suit with the dilute nature of the MWW. Moreover, a high C/N ratio of 64.9 explains its abundance of carbon content hence suitable for elevating the C/N ratio of MWW. Results from this study showed only small quantities of modifier ≤ 10% were needed to adjust the C/N ratio of MWW from 10.6:1 to 30.4:1. It also causes variation of TS from 2.77% to 10.7% as shown in Table 5. Sugar cane molasses cause large impact in elevating the C/N ratio and TS compared with many other substrates used for the codigestion of municipal wastewater sludge (Heo, Park, & Kang, 2004 ; Zitomer, Adhikari, Heisel & Dineen, 2008) .

Table 5: Characteristics of the modified substrates

Batch experiments	Amount of modifier (mL) in 1000mL of substrate mixtures	C/N Ratio	Total solids (%)	Total solids (g/L)	Volatile solids (g/L)
1	0	10.6	2.77	2.23	1.76
2	20	15.7	4.34	10.86	9.24
3	40	20	5.94	19.48	16.72
4	60	23.8	7.52	28.11	24.2
5	80	27.1	9.12	36.73	31.68
6	100	30.4	10.7	45.36	39.17

4.4 The biogas production, yield and methane content at different total solids loading levels

The environment of the microorganisms in the reactor determines the performance of anaerobic digestion systems (Chen *et al.*, 2016). This is because biogas production is directly proportional to the growth of methanogenic bacteria (Nopharatana, Pullamma & Clarke, 2007). In the present study, numerous cumulative volume of biogas was obtained at different TS levels (Fig. 8). The modified substrate of 7.52% TS corresponding to a C/N ratio of 23.8 had the highest cumulative biogas production while the least biogas production was obtained at 4.34% TS corresponding to a C/N ratio of 15.7. However, this was 3.4 times higher than the biogas yield from the anaerobic digestion of MWW alone with 2.77% TS and 10.6 C/N ratio. These results are similar to those from another study where the biogas produced from vinasse that had high COD and TS of about 7.015% was also the highest biogas producer (Budiyono & Sumardiono, 2014).

These results also demonstrate that when the TS are higher than 7.52 %, the biogas yields are lower. This is probably due to overloading in the digester which led to instability of anaerobic digestion and hindrance of methanogenic bacteria which digest the carbons from the feedstock (Liu & Lv, 2016; Aboudi, Álvarez-Gallego & Romero-García, 2017). It should however be noted that the optimum loading observed is not universal but depends on the reactor organization and other operating conditions (Dhar *et al.*, 2016). Literature also showed that, if the amount of TS is high in the digester, there could be over-accumulation of organic matter and blockage of the digestion process. Furthermore, if the amount of water is high, there can be less organic matter in the digester and low biogas production (Liu & Lv, 2016). Therefore, for maximum digestion of substrates, the TS must be at an optimal concentration (Song *et al.*, 2010; Lin *et al.*, 2011).

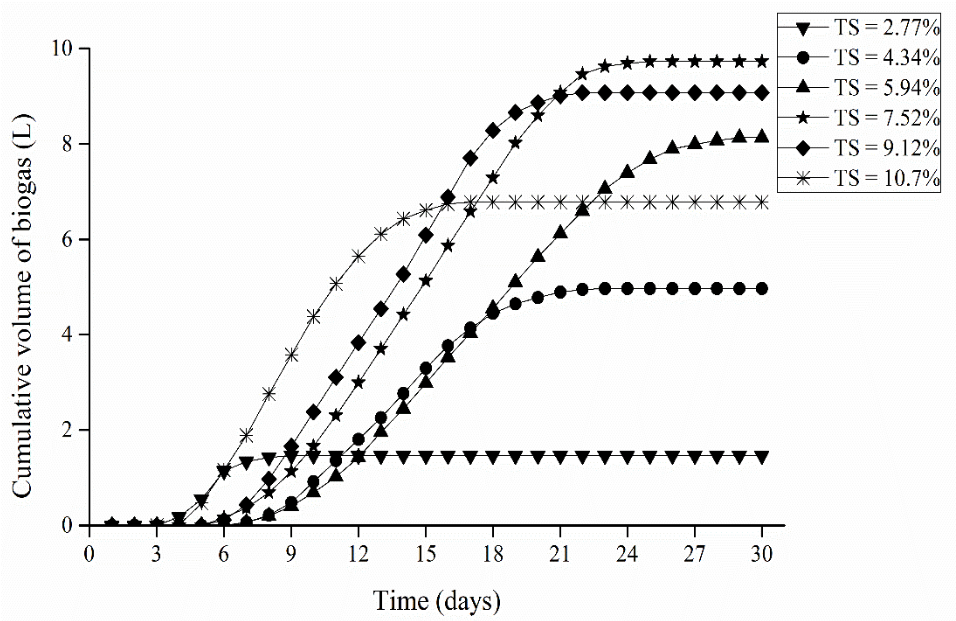

Figure 7: Cumulative biogas volume at various TS levels as a function of time

From the study, it was observed that as TS was increasing the lag phase was lengthened, this indicate the increase of time needed for methanogens to acclimatize in the new environment. Also stationary phase was reduced which indicate the over loading of the anaerobic system as shown by Fig. 9.

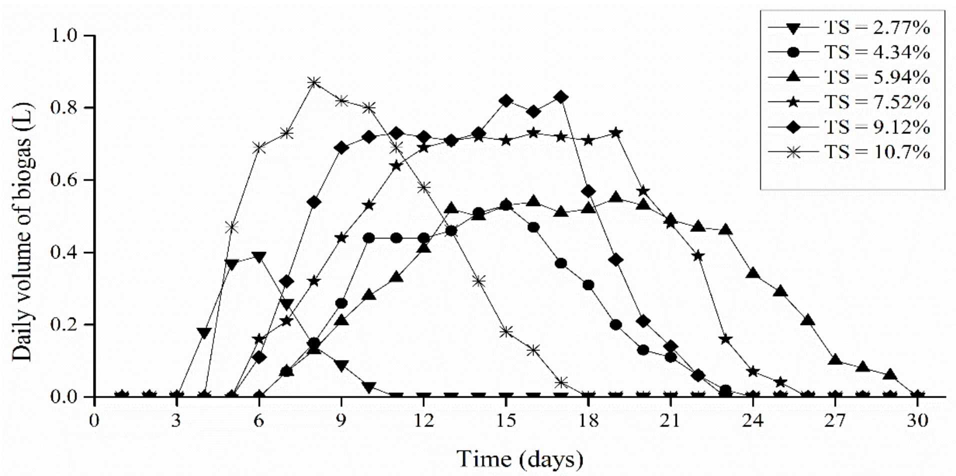

Figure 8: Daily production of biogas from different total solids (TS) loading levels

The calculated biogas yield from the modified substrates operated at the TS concentration of 10.7%, 9.12%, 7.52%, 5.94% and 4.34% were 101, 172, 297,344 and 379 mL/g COD respectively by the end of digestion process. About 94.8%, 58.1%, 45.4%, 30.1% and 55.7% of total biogas yield was achieved after the first 14 days of digestion. The biogas yields obtained in this study are larger than the biogas yields obtained from the anaerobic digestion of the municipal wastewater sludge as reported by (Bougrier, Delgenes & Carrere, 2006; Khan *et al.*, 2011) and similar to the one obtained from the co-treatment of MWW with food waste (Guven *et al.*, 2019).This shows the positive effect of codigesting MWW for higher biogas yield. However, there is scarce information of the codigestion of the MWW with other organic waste for biogas production. The average methane contents of the biogas were 55.6%, 57.3%, 63.1%, 61.7%, and 69.1% from 5 modified substrates with 10.7%, 9.12%, 7.52%, 5.94%, and 4.34% TS respectively. The lower biogas and methane yield when the TS concentration was ≥ 7.52% indicate that there was inhibition of methanogenic bacteria.

4.5 The optimal carbon to nitrogen ratio for the co-digestion

The carbon to nitrogen (C/N) ratio for the maximum biogas production is known to vary from 20:1 to 30:1 with its optimal value of 25:1 in mesophilic temperature range (Wang *et al.*, 2012; Dioha *et al.*, 2013). High or low C/N ratio lower the biogas production, this was avoided in the present study through co-digestion of SCM (modifier) with high C/N ratio and MWW with low CN ratio as they were shown in Table 5. Thus, the cumulative biogas production was 6.7 times higher at the optimum C/N ratio of 23.8:1 than that of C/N ratio of 10.6:1 of MWW. Higher biogas yield at C/N ratio of 23.8 was attributed by 94(v/v %) of MWW and 6(v/v %) of the modifier. The obtained optimal C/N ratio falls within the range even though it diverts from 25:1 this is because anaerobic co-digestion for higher biogas yield depends on the type of waste used in codigestion (Wang *et al.*, 2012). The maximum cumulative biogas yield increased with C/N ratio to an optimum value and then decreased as shown in Fig. 10. The results from other studies shows the optimal C/N ratio of the substrates varies even though it's very rarely to be less than 15 (Yan *et al.*, 2015; Zhang *et al.*, 2016). The polynomial curve plot fitted on the graph with the Adj. R-Square of 96.4%.

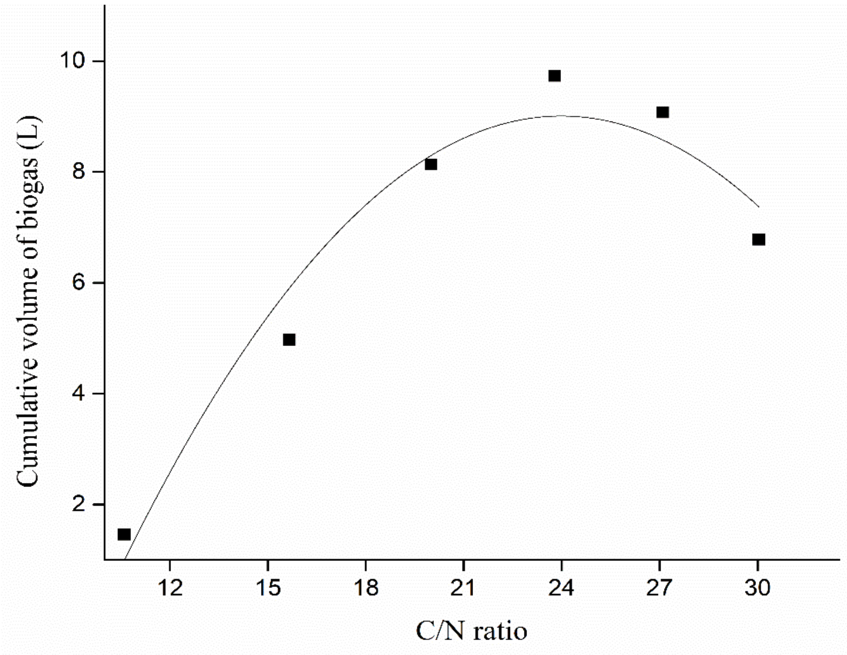

Figure 9: The maximum cumulative biogas volume as a function of C/N ratio

4.6 Effect of modified substrate mixing ratios on the stability of anaerobic digestion

The range of pH and accumulation of VFA in biodigesters are important parameters that determine the stability of the anaerobic digestion process (Siegert & Banks, 2005; Chen *et al.*, 2012). In this study Fig. 11 showed that the initial pH of reactors were in the tolerable range approximately 7.46, 7.37, 7.17, 7.43, 7.47, and 7.30 for 10.7%, 9.12%, 7.52%, 5.94%, 4.34%, and 2.77% respectively. During the anaerobic digestion process less pH fluctuations were experienced in the anaerobic digestion of MWW only with TS of 2.77% as it was adjusted only once and remained within the permissible limits of 6.3 to 7.8 even at the end of the digestion process. However, for the SCM modified substrates, pH was observed to increase with increasing TS concentrations. There were high pH fluctuations in the reactors with 7.52%, 9.12% and 10.7% TS which persisted and had to be adjusted until approximately after 14 days as shown by Fig. 11. However, it should be noted that without pH adjustment, the decrease in pH in modified substrates is enough to affect the methanogenic activities as it dropped below the established minimum suitable range of 6.3 to 7.8 (Khalid *et al.*, 2011). This indicates the difficulty of producing a high amount of biogas from single-stage anaerobic co-digestion of the substrate used in this study without adjusting the pH. The addition of alkali is recommended for pH adjustments to minimize hydrolysis and to stabilize the methanogenic process.

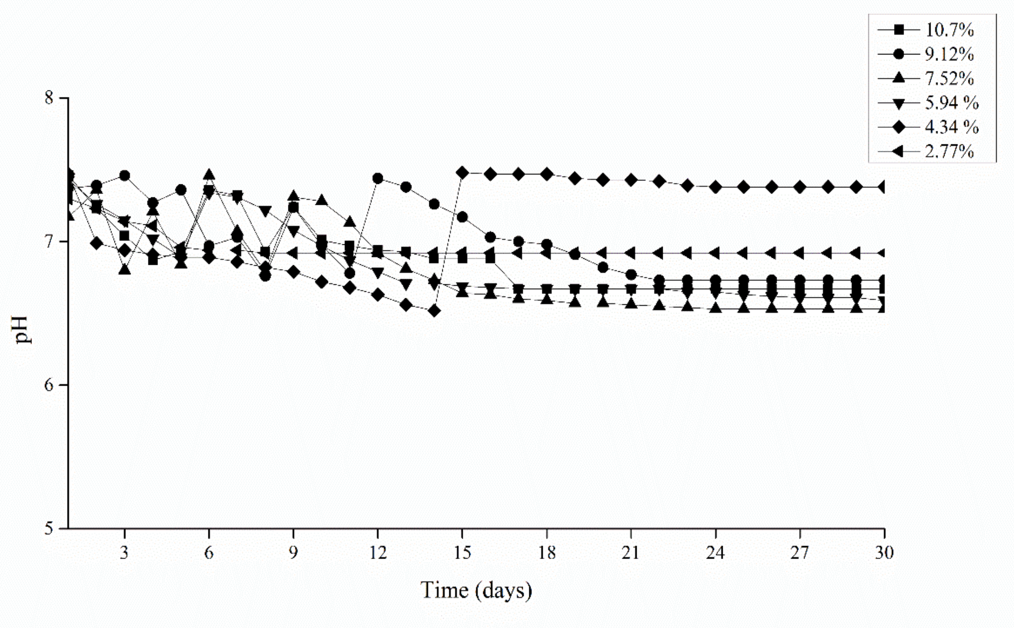

Figure 10: pH variation at various percentage modifiers

The present study also showed that VFA/alkalinity of digestate substrates with TS 10.7%, 9.12%, 7.52%, 5.94%, 4.34%, and 2.77% were 1.01, 0.83, 0.82, 0.34,0.11, and 0.23 respectively as shown by Table 6. The VFA to alkalinity ratio for various TS concentrations (≤ 5.94%) ranged from 0.11 to 0.34 which indicates that the relative stability of the digesters. While the substrate mixture with VFA/Alkalinity ratio ≥ 0.82 inclined to digester instability. This might be caused by high TS concentrations which took a long time for hydrolysis hence VFA accumulation in the system. This is supported by other studies which suggest the VFA/alkalinity ratio should be maintained below 0.4 for the stability of anaerobic digestion (Kameswari, Kalyanaraman, Porselvam & Thanasekaran, 2012). Nevertheless, other studies have shown huge variations of optimum VFA between different substrates used in anaerobic digestion (Banks & Wang, 1999; Chen *et al.*, 2012; Liotta *et al.*, 2014). In the present study, alkalinity was in the range of 2386 to 3406.8 mg/L in the reactors (Table 6); it was within the range of 2000 - 4000 mg/L which required for digesters to perform under stable conditions (Velmurugan, 2011). However, the accumulation of VFA to above 920 mg/L was sufficient to inhibit the buffering capacity of alkalinity.

Table 6: Levels of acidity and alkalinity in digestate

TS (%)	VFA(mg/L)	Alkalinity(mg/L)	VFA/Alkalinity
10.7	2410	2386	1.01
9.12	1974.7	2370.1	0.83
7.52	1837.4	2240.7	0.82
5.94	920.2	2706.5	0.34
4.34	334.4	3040.7	0.11
2.77	783.6	3406	0.23

4.7 Effect of substrates modification on residual chemical oxygen demand

The reduction of Chemical oxygen demand (COD) was examined by considering the level of biodegradability within the reactors. In this study COD of the digestate was high in the substrate mixtures with large TS contents and the COD removal efficiency was observed to increase from 10.7%, 9.12%, 7.52%, 5.94% to 4.34%, with the reduction efficiency of 45.83%, 49.62%, 69.2%, 76.69% and 87% respectively as shown in Fig. 12. Since the energy capture step in this study is integrated with the treatment of MWW, it is not desirable to have too high COD residue as it can interfere with the treatment needed for the wastewater to meet environmental compliance standards. The substrate mixture with 4.34% TS was recommended in this study because of its lower COD residue in the effluent (1.8g/L) and lesser pH fluctuations. Also its removal efficient of 87.02% is higher compared to the other study on co-treatment of municipal wastewater and food waste where the maximum of 63% of COD removal was achieved (Guven *et al.*, 2019). The higher residual COD was probably due to the accumulation of high levels of organic materials in the biodigester. As a result, methanogens can be inhibited through overproduction of VFA in the anaerobic reactor (Dhar *et al.*, 2016).

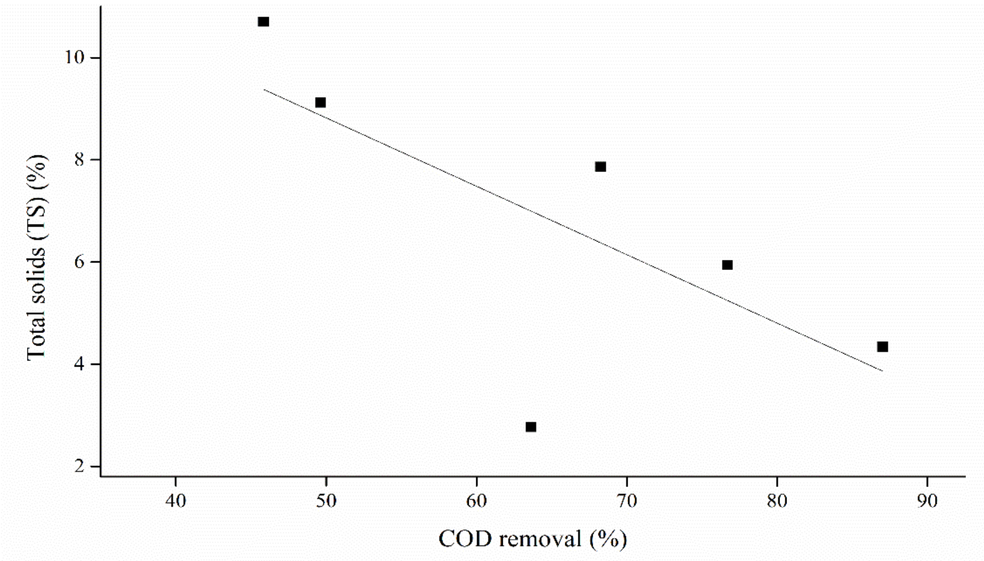

Figure 11: Correlation of the TS (%) on COD removal efficiency (%)

4.8 Estimation of energy recovery from anaerobic digestion of modified Moshi municipal wastewater

The estimation of the potential heat and electricity production from the biogas was calculated from the results obtained from the anaerobic digestion of the modified substrate with 4.34% TS and 15.7 C/N ratio due to the aforementioned reasons. The average daily inflow was 4221 m^3/d. The information used for the estimation of the possible daily electricity and heat production is shown in Table 7.

Table 7: Estimation of annual heat and electricity production from the produced biogas

Data needed	Value	Source/basis
Average daily amount of the MWW received	4221 m^3/day	Measured flow rate (MUWSA).
Total daily SCM needed	92.9 m^3/day	Mixing ratio of 2% v/v in substrate mixture
Biogas production from 1 batch reactor	23537 m^3	1 L of substrate mixture produces 4.97 L of biogas
Energy content of pure methane	Heat energy =39.8 MJ/m^3 Electrical energy = (11.06 kWh/$m^{3)}$	Jørgensen (2009).
Average methane content of the generated biogas	69%	Mixing ratio of 2%v/v in substrate mixture
Heat energy efficiency of CHP engines	45-50%	
		(Jørgensen, 2009)
Electrical energy efficiency of CHP engines	35-40%	

The Moshi municipal wastewater in Tanzania, with the annual generation of the modified substrate of 662 973 m^3 is anticipated to generate about 16 241 m^3 of methane through the anaerobic decomposition. If the gas turbines which use the combined power and heat engine (CHP) with the efficiency of 35% used, up to 1.8 GWh/year could be produced. The 5MW

CHP engine with 10 working hours per day could be installed with such amount of electricity.

The estimated amount of electricity was smaller compared to the 79 GWh/year produced from sisal fibres waste generated annually in Tanzania (Mshandete *et al.*, 2006). Also small compared to 14 GWh/year which estimated from co-treatment of MWW and food waste as reported by (Guven *et al.*, 2019). However, it was not far from the 2.4GWh/year estimated from the waste produced by Serengeti breweries (Nassary & Nasolwa, 2019). These differences might be caused with the conversion technology used which reflected electrical energy only and not with thermal energy as it was considered in this study, conversion efficiency considered and the methane yield which varies from one feed stock to another. The produced electricity estimated in this study can reduce the energy demand in the country based on the fact that Tanzania is electrical energy-deficient with plans to increase the installed power capacity from 1564 MW to about 10 x 10^3 MW by 2025 (Sumari, Shao & Kira, 2018). Together with electrical energy, 8193 GJ/year was estimated. This was comparable with the other study done by (Nassary & Nasolwa, 2019). Even though many studies does not consider the production of thermal energy in biogas plants but is the valuable energy for water or space-heating to maintain the mesophilic or thermophilic temperatures for enhancing the optimal production of biogas.

When the electrical energy produced from the MWW compared to the other fuels using UnitJuggler unit converter, it was corresponding to 152 192.6 kg, 16 905.4 m^3, 217 444 kg, or 382 289.4 kg of fuel oil, natural gas, hard coal, or firewood respectively. This explains the significant of using MWW as a source of renewable energy which can reduce the use of fossil fuel which are depleted with time, unsustainable and cause environmental problems.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The increase of energy demand globally and the need of environmental protection expand the requirement of renewable sources of energy including anaerobic digestion of waste. The present study reveals the possibility of using small quantities of a modifier with a high C/N ratio to improve the biogas yield from MWW anaerobic digestion. The highest biogas production of 9.73 L/L of modified substrate was obtained from the substrate mixture with 6% of SCM as a modifier although high COD of the digestate and pH instability were the main challenges. This study recommends the use of substrate mixture containing modifier (2%), TS (4.34%) and C/N (15.6) with the biogas production (4.97 L/L of modified substrate). Its lower COD (1.8 g/L) of digestate, low pH fluctuation and low VFA /alkalinity ratios support its recommendation because the aim was to integrate energy recovery step with MWW treatment. The produced biogas was estimated to produce 16 241 m^3 of methane which is equivalent to 1.8 GWh and 8193 GJ per annum. This showed that the use of CHP engine for the conversion of biogas to heat and electrical energy increases the energy value of the wastewater and can be an incentive for wastewater treatment companies. Also biogas is among of the impending fuel if the modern technology of its production and use are applied. Therefore, investment on anaerobic digestion with electricity generation is needed because the renewable energy policy aligns with the available policies worldwide.

5.2 Recommendations

(i) Energy recovery from the municipal waste water (MWW) can be achieved through the co-digestion with the organic materials rich in carbon and low amount of moisture for stance sugarcane molasses (SCM).

(ii) Further studies needed to find other organic materials with high carbon content for co-digestion with MWW to obtain higher biogas yield with lower COD residue.

(iii) Therefore, investments in energy recovering system from municipal wastewater treatment plants is encouraged as it observed to be a promising source of energy.

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